

Initial state fluctuations and final state correlations: Status and open questions

Andrew Adare¹, Matthew Luzum^{2,3,4} and Hannah Petersen^{5,6}

¹ Yale University, Department of Physics, New Haven, CT 06520, United States

² Institut de physique théorique de Saclay (CNRS URA2306), F-91191
Gif-sur-Yvette, France

³ McGill University, 3600 University Street, Montreal QC H3A 2TS, Canada

⁴ Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

⁵ Department of Physics, Duke University, Durham, North Carolina 27708-0305,
United States

⁶ Frankfurt Institute for Advanced Studies, Ruth-Moufang-Strasse 1, 60438 Frankfurt
am Main, Germany

E-mail: aadare@cern.ch

E-mail: mluzum@physics.mcgill.ca

E-mail: petersen@fias.uni-frankfurt.de

Abstract. The recent appreciation of the importance of event-by-event fluctuations in relativistic heavy-ion collisions has lead to a large amount of diverse theoretical and experimental activity. In particular, there is significant interest in understanding the fluctuations in the initial stage of a collision, how exactly these fluctuations are propagated through the system evolution, and how they are manifested in correlations between measured particles. In order to address these questions a workshop was organized on “Initial State Fluctuations and Final State Correlations”, held at ECT* in Trento, Italy during the week of 2–6 July, 2012. The goal was to collect recent work in order to provide a coherent picture of the current status of our understanding, to identify important questions that remain open, and to set a course for future research. Here we report the outcome of the presentations and discussions, focusing on the most important conclusions.

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1. Introduction

Relativistic heavy-ion collisions probe the extreme high-temperature regime of the strong interactions. Specifically, the main goal is to create and characterize a deconfined state of matter, the quark-gluon plasma (QGP) and investigate the nature of a deconfinement phase transition. The Relativistic Heavy Ion Collider (RHIC) has been studying these topics experimentally since 2000, and was joined in November 2010 by the Large Hadron Collider (LHC) with Pb+Pb collisions at an order of magnitude higher energy than the highest studied at RHIC.

Since the first data were taken at RHIC, one of the most important experimental signatures of the QGP has been the azimuthal anisotropy in correlations between detected particles. In particular, the large value of the so-called ‘elliptic flow’ observable, indicating strong collective behavior of the collision system, has been one of the most important and most studied measurements. It provided one of the strongest pieces of evidence leading to the conclusion that a strongly-coupled, low-viscosity, QGP medium is created in these collisions.

Elliptic flow refers to a second Fourier component of the azimuthal distribution of emitted particles. When two identical nuclei collide at a finite impact parameter, the overlap region is an oblong shape in the transverse plane. In the standard picture, the system comes to an approximate local equilibrium and expands according to (viscous) hydrodynamics. The elliptic asymmetry in the initial state is transformed during the collective expansion into an asymmetry in the final momentum distribution of the detected particles. The efficiency of this transformation is sensitive to medium properties such as viscosity.

Random variations in the initial distribution of nucleons, due to quantum fluctuations, lead to event-by-event fluctuations in the initial geometry. Naively, in a symmetric collision system, odd harmonics in the azimuthal momentum distribution are expected to be negligible. It has only recently been realized that these fluctuations are not, in fact, negligible, and that by taking them into account one might potentially explain all long-range pair correlation data, which were previously not understood. Further, with this realization come new potential ‘flow’ observables — not only the natural extension of elliptic flow measurements to odd harmonics such as triangular flow, but also a large number of other correlations.

These new measurements have the potential to provide tight constraints on theory and to extract precise quantitative properties of the QGP, as well as to shed light on the (as-yet poorly understood) non-equilibrium QCD dynamics of the initial stage of the collision. The overall aim of the workshop was to construct a consistent picture of the current understanding of the community and set a course for future investigation. Specific questions that were addressed during this workshop include:

- What is the best model for the initial state? What constraints can we already put on it from new data?

- How exactly is the initial spatial anisotropy converted to final-state momentum anisotropy? Can we understand the hydrodynamic response in general, or do we need to run event-by-event hydrodynamic simulations for every candidate initial condition?
- What is the current uncertainty in the viscosity of the QGP, and what is the best strategy for reducing it?
- What else can the newly-measured observables teach us, and what other observables should be measured?
- What are the prospects for experimentally and/or theoretically distinguishing between initial-state and collective effects?
- Can one disentangle various sources of fluctuations?

In the following we summarize the presentations and discussions at the workshop keeping the above formulated set of questions as a guideline. In section 2 the understanding of the initial state is described in more detail. Section 3, contains the present analysis of the hydrodynamic response and the extraction of transport coefficients. In section 4 the challenges in comparing theoretical calculations with experimental measurements in a meaningful fashion are highlighted. Finally, section 5 outlines a set of new observables that will enhance our understanding of hot and dense QCD matter. Note that we do not aim to provide a comprehensive review, but only offer highlights. The slides from all talks can be obtained from [1].

2. Initial Conditions

There is no longer any question that fluctuations in the initial conditions are crucial for a complete understanding of the bulk properties in heavy ion collisions [2]. The most basic way to model these fluctuations is to choose random positions for nucleons in each nucleus before the collision, and deterministically calculate the resulting post-collision energy density according to some prescription. This is what is done, e.g., in a standard Monte Carlo Glauber or Monte Carlo KLN model, which have been commonly used in the past.

Although it is possible that this captures a significant part of the fluctuations in the initial transverse density, it is not sufficient for the type of quantitative comparison to data that will be necessary. Within the last two years, there has been tremendous progress in the development of more realistic initial state descriptions. A wealth of different incarnations of the aforementioned Glauber and KLN model have been studied, e.g. including the fluctuations in the energy deposition per binary collision [3] or taking into account a realistic wounding nucleon profile and the nucleon-nucleon correlation correlations [4, 5]. In addition, many groups use dynamical transport approaches to describe the initial non-equilibrium evolution of the heavy ion reaction [6, 7, 8, 9].

With all of this work ongoing, it is important to emphasize that there is not a binary choice between two well understood competing models for the initial condition

(e.g., 'Glauber' versus 'CGC'), as is sometimes inferred by those not directly involved in this research, but instead there exists a large space of possible physical pictures, parameters, and implementations. For example, the Color-Glass-Condensate framework is not synonymous with only the particular MC-KLN model, but many implementations exist of CGC-based, Glauber-based, and other ideas. As such it is also important for researchers to specify the initial state model they employ with all necessary details including all the sources of fluctuations that are taken into account. Once the ingredients are better understood and there is a consensus reached on how to implement the fluctuations and geometry, it would be beneficial for standardized versions of the models to be made available to the public.

The following sources of fluctuations were studied here:

- Fluctuations in the positions of the nucleons (or quarks) and their binary interactions
- Finite extent of the nucleons and correspondingly adjusted Wood-Saxon distributions
- Fluctuations in the initial momentum distribution (initial flow)
- Local fluctuations in energy deposition/particle production

One of the key points that has been discussed in detail at the workshop is that the multiplicity distributions in proton-proton collisions provide an important constraint for the latter source of fluctuations. There is no unambiguous mapping of the fluctuations in p-p collisions to systems with higher nucleon density, but any realistic model should be able to reproduce the multiplicity distribution in the p-p limit.

Often, the discussion of the initial state profiles has been restricted to the transverse plane, but the matter produced in heavy ion collisions has three spatial directions. Since there are more and more 3+1 dimensional (viscous) hydrodynamic codes in use, it is definitely time to pay more attention to the longitudinal direction. There have been a few exploratory studies on longitudinal fluctuations [10, 11], but a comprehensive understanding is still missing. The η and $\Delta\eta$ dependence of particle correlations can lead to useful insights in that respect.

The initial non-equilibrium evolution is still one of the main open questions in the field. Recently, there was a new promising attempt using SU(3) Yang-Mills field evolution by the BNL group [12]. It will be particularly interesting to see if rapid thermalization can be obtained within this framework by including quantum fluctuations in a full 3+1D simulation.

Since the initial evolution produces finite initial velocity fields, a complete energy-momentum tensor including shear stress components should be used to initialize the hydrodynamic evolution. There are a few studies on the influence of initial flow in the system, but a consensus on its size and importance has not been reached yet.

At the moment, the primary means of characterizing initial state profiles is calculation of the first few coefficients of the Fourier expansion in coordinate space (ϵ_n). It needs to be explored whether there are other quantities that are suitable for

representing the longitudinal direction, the initial velocity profile and other features in a more complete way.

Overall, the main task at hand is to constrain the scale of the fluctuations exemplified by flux-tube radius, gaussian width, and the amplitude of fluctuations or correlation length [13] in connection with a specific physics assumption. Now that it has become clear that quantum fluctuations are important to understand the full evolution of heavy ion reactions, there is the opportunity to pin down the highly excited nuclear initial states and its properties.

3. Hydrodynamic Response

After this initial stage of a heavy-ion collision, the system continues to evolve, expanding collectively in response to these initial conditions. This evolution is usually modeled with hydrodynamics or transport calculations, many of which were presented at this workshop. Several important themes emerged from numerical simulations as well as analytic work.

One emerging theme was a more comprehensive theoretical study of experimental data. In the past, a few observables were commonly calculated and studied individually. In the future it will be necessary to describe multiple observables from a single calculation, as well as to do so in more detail. At a minimum, a simultaneous description of multiple flow harmonics $v_n\{2\}$ is needed as a function of transverse momentum and centrality, with even more information contained in higher cumulants [14]. Especially challenging is a combined understanding of hard and soft physics, allowing for a description over a large range in transverse momentum [7].

However, measurements that are even more differential are also possible (and available). For example, a measurement like $v_2\{2\}$ is obtained by measuring azimuthal correlations between pairs of particles, but a single such measurement typically contains an average over the mean and relative pseudorapidity of the pair (within some range), as well as the transverse momentum of one or both particles, and disregarding information about other properties such as electric charge. Nevertheless, more detailed dihadron correlation data are available to be studied.

In this workshop we saw progress in understanding how structures in relative pseudorapidity can arise from longitudinal fluctuations in the initial state [9, 10, 15], from intrinsic fluctuations generated during hydrodynamic evolution [16], or from charge balancing that result in a differing structure for like-sign and opposite-sign pair correlations [17, 18]. In addition, progress was presented in the study of fluctuations in multiplicity and transverse momentum [18, 19]. Most of these studies focussed on charged hadrons, but electromagnetic probes also give valuable independent information [20].

Looking beyond two-particle correlations allows for a significantly expanded space of independent of observables. One particularly exciting development was the large set of recent measurements of correlations between mixed harmonic event planes from

the ATLAS collaboration [22], compared to brand new event-by-event hydrodynamic calculations [23].

Motivated by the large uncertainties that still remain in the initial conditions, another emerging theme is the characterization of the medium response in a general way. A more detailed understanding of hydrodynamic response to initial conditions, as well as a precise determination of which aspects of the initial conditions each observable is most sensitive to, would allow for significant constraints to be placed on the properties of the initial conditions [24] and medium properties [25]. Exploring the scaling properties of flow observables may also help to understand system properties [26].

Event-by-event hydrodynamic calculations have suggested that v_2 and v_3 can be accurately predicted in any given event by an eccentricity ε_2 and triangularity ε_3 in the initial transverse energy density profile, while v_4 and v_5 do not follow such a simple relation [27]. This observation motivated a quantitative study of which definitions of ε_2 and ε_3 are the best predictors of final-state anisotropy, as well as a result that v_4 (v_5) arises as a linear combination of ε_4 and ε_2^2 (ε_5 and $\varepsilon_2\varepsilon_3$) [6]. This knowledge can be exploited by simulating only as many events as necessary to calculate the coefficient in front of each term, which allows systematic study of the importance of each term as a function of, e.g., p_t and viscosity. Additionally, various predictions are made possible without the use of full event-by-event calculations [28]. An open question remains as to how far this can be pushed — e.g., can one reproduce all of the mixed harmonic event plane correlations without resorting to brute force event-by-event calculations?

4. Comparison of Theory Calculations to Experimental Data

There has been a wealth of new measurements of higher anisotropy coefficients and other particle correlation observables presented at the workshop, e.g [22, 29, 30, 31]. Some questions arose as to how a meaningful comparison to theory calculations can and should be performed, which is crucial for any quantitative statements about the transport coefficients of the quark gluon plasma.

The first issue to be addressed is the definition and selection of centrality categories. Theoretical calculations are often carried out at a specific impact parameter or in a range of impact parameters. This quantity is not directly accessible experimentally, but centrality classes are defined by the number of charged particles produced at mid- or forward rapidity, or by the number of spectators measured in a veto calorimeter. Usually the parameters in initial state models are tuned such as to reproduce the measured number of final-state particles in central collisions. Parton-hadron duality is sometimes assumed in order to relate the initial number of gluons to the final number of pions. This mapping procedure needs to be carefully cross-checked, especially when the evolution is dissipative and the entropy increases. Differing centrality selection criteria can significantly influence the results, and any assumptions relating the impact parameter to the number of gluons and the final particle yields needs to be verified. A conclusion from the workshop was that the centrality determination procedure should

be stated clearly when results are presented.

The second emphasis of the discussions at the workshop was more specifically related to flow observables. For an apples-to-apples comparison it is important to be aware of the different measurement methods and what they actually imply. In pure hydrodynamic calculations where observables are obtained by integrating over the Cooper-Frye hypersurface, one can calculate an exact value for v_n in each event and therefore any possible event-averaged moment, e.g., the root mean square (RMS) value which can be compared to a 2-particle correlation measurement of v_n . If a finite number of particles are sampled on the hypersurface that are potentially propagated through a hadron cascade, one must use procedures analogous to experimental analyses, such as the scalar product method, 2-particle correlation method or the cumulant method which can be compared directly to the relevant data. It is important to note, however, that the standard event plane method only gives the same result as the corresponding experimental measurement if the resolution of the event plane is the same in both cases.

Keeping in mind caveats such as this, the best way to make a meaningful comparison between theoretical calculations and experimental data is to employ the same analysis as used by the experiments. The first step is to define the centrality classes in the same way as the specific collaboration. The MIT group (CMS) and Ante Bilandzic (ALICE) have expressed interest in collaborating with theoreticians to provide them with stand-alone software which can be used for the analysis of final state particle distributions. The first package with the cumulant analysis developed by the ALICE collaboration is currently being tested.

5. Outline of Future Measurements

One of the discussion sessions during the workshop has been devoted to future experimental measurements and requests to the theory community. The extensive factorization tests of two-particle correlations ($V_{n\Delta}$) over a large range of trigger and associated particle transverse momentum as carried out by the LHC collaborations are useful to distinguish bulk anisotropies from other/non-flow contributions, as well as to study flow fluctuations. Similar analyses can be done in the space of trigger and associated pseudorapidity. Measurements of v_n coefficients with respect to an event plane of different order Ψ_m with $m \neq n$ are sensitive to the hydrodynamic response and give insights about mode-mixing. Reconstructing the Ψ_1 event plane that corresponds to the rapidity-even v_1 observable would be desirable. Another measurement that could provide insights into the interplay of jet-medium response and pure bulk evolution effects is to analyse the untriggered two-particle correlations in events that contain a 50-100 GeV jet and compare the result to the minimum bias one. One issue that might complicate such a measurement is to find a consistent centrality selection, since the requirement of a high momentum jet biases the event sample.

The wish-list for the theory community is to calculate for example 3-particle correlations with a high transverse momentum (6–8 GeV) trigger particle and associated

particles below ~ 2 GeV in all different combinations of angular spaces, i.e. $\Delta\phi - \Delta\phi$, $\Delta\phi - \Delta\eta$ and $\Delta\eta - \Delta\eta$. As a baseline the correlation functions from a medium evolution only would be interesting already. Otherwise, these multi-particle calculations are the most promising way to disentangle jet-medium effects from the underlying pure medium response, if such a distinction makes sense. The meaning of the event-plane correlations as measured by the ATLAS collaboration should be investigated further by more theory comparisons. In addition, more theoretical effort needs to be spent on calculating other fluctuation observables, such as $\langle p_T \rangle$ fluctuations, that have sensitivity to the number of sources in the initial state. Not all theory groups are able to address these types of observables, since very high statistics are required which corresponds to a huge amount of CPU time in event-by-event hybrid approaches. Another goal that might be easier to reach is to perform calculations of higher harmonic flow coefficients at lower beam energies, since there are now results available from the low beam energy scan at RHIC, as well as for other nuclei (copper and uranium). The flow results for identified particles should also be addressed by more theoretical calculations.

6. Conclusions and Outlook

All known sources of fluctuations should be included in models of the initial stages of heavy-ion collisions. In particular, implementations of fluctuations in particle production into Monte Carlo models should be continued, making sure to obey experimental constraints like multiplicity distributions in proton-proton collisions, and differences in recent implementations should be better understood. Much progress has been made in characterizing the hydrodynamic response to the initial conditions in terms of simple relationships between properties of the initial density and flow correlations in the final particle distributions. This is providing us with important insight, but it is an open question how far this can be taken and whether brute-force event-by-event calculations will always be necessary for describing certain data. More standardization is necessary in the field. Examples include definitions of initial anisotropies ϵ_n , variations of Glauber Monte Carlo models, and experimental flow analyses. Subtleties are present in comparing theoretical calculations to experimental data and more care needs to be taken in the future in order to compare the correct quantities. Some possibilities for future measurements and a wish-list for the theory community have been presented in Section 5.

This workshop was very timely, coming at the confluence of major theoretical and experimental developments resulting in a high degree of productiveness and in the generation of important new ideas summarized here, which we expect to be worked out during the coming few years.

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References

- [1] Slides from each workshop presentation can be found at the website for ECT*: <http://www.ectstar.eu/>
- [2] B. Alver and G. Roland, Phys. Rev. C **81** (2010) 054905 [Erratum-ibid. C **82** (2010) 039903] [arXiv:1003.0194 [nucl-th]]; Presentation by G. Roland
- [3] A. Dumitru and Y. Nara, Phys. Rev. C **85**, 034907 (2012) [arXiv:1201.6382 [nucl-th]]; Presentation by A. Dumitru and Y. Nara
- [4] W. Broniowski and M. Rybczynski, Phys. Rev. C **81**, 064909 (2010) [arXiv:1003.1088 [nucl-th]]; M. Rybczynski and W. Broniowski, Phys. Rev. C **84**, 064913 (2011) [arXiv:1110.2609 [nucl-th]]; Contributed in discussion by W. Broniowski
- [5] M. Alvioli, H. Holopainen, K. J. Eskola and M. Strikman, Phys. Rev. C **85**, 034902 (2012) [arXiv:1112.5306 [hep-ph]]; Presentation by M. Alvioli
- [6] F. G. Gardim, F. Grassi, M. Luzum and J. Y. Ollitrault, arXiv:1203.2882 [nucl-th]; F. G. Gardim, F. Grassi, M. Luzum and J. -Y. Ollitrault, Phys. Rev. C **85**, 024908 (2012) [arXiv:1111.6538 [nucl-th]]; Presentation by J. Y. Ollitrault
- [7] K. Werner, I. Karpenko, T. Pierog, M. Bleicher and K. Mikhailov, Phys. Rev. C **82**, 044904 (2010) [arXiv:1004.0805 [nucl-th]]; K. Werner, I. Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais, Phys. Rev. C **85**, 064907 (2012) [arXiv:1203.5704 [nucl-th]]; K. Werner, Phys. Rev. Lett. **109**, 102301 (2012) [arXiv:1204.1394 [nucl-th]]; arXiv:1205.3379 [nucl-th]; Presentation by K. Werner
- [8] H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stoecker, Phys. Rev. C **78**, 044901 (2008) [arXiv:0806.1695 [nucl-th]].
- [9] L. Pang, Q. Wang and X. N. Wang, Phys. Rev. C **86**, 024911 (2012) [arXiv:1205.5019 [nucl-th]]. Presentation by L. Pang
- [10] Presentation by S. Gavin
- [11] Presentation by A. Poskanzer
- [12] B. Schenke, P. Tribedy and R. Venugopalan, Phys. Rev. Lett. **108**, 252301 (2012) [arXiv:1202.6646 [nucl-th]]; B. Schenke, P. Tribedy and R. Venugopalan, arXiv:1206.6805 [hep-ph]; Presentation by B. Schenke
- [13] B. Muller and A. Schafer, Phys. Rev. D **85**, 114030 (2012) [arXiv:1111.3347 [hep-ph]]; Presentation by B. Müller
- [14] T. Hirano, P. Huovinen, K. Murase and Y. Nara, arXiv:1204.5814 [nucl-th]; Presentation by K. Murase
- [15] J. Xu and C. M. Ko, Phys. Rev. C **83**, 021903 (2011) [arXiv:1011.3750 [nucl-th]]; Phys. Rev. C **83**, 034904 (2011) [arXiv:1101.2231 [nucl-th]]; Phys. Rev. C **84**, 014903 (2011) [arXiv:1103.5187 [nucl-th]]; Phys. Rev. C **84**, 044907 (2011) [arXiv:1108.0717 [nucl-th]]; Presentation by C. M. Ko
- [16] J. I. Kapusta, B. Muller and M. Stephanov, Phys. Rev. C **85**, 054906 (2012) [arXiv:1112.6405 [nucl-th]]; Presentation by M. Stephanov
- [17] P. Bozek and W. Broniowski, Phys. Rev. C **85**, 044910 (2012) [arXiv:1203.1810 [nucl-th]]; P. Bozek, W. Broniowski and J. Moreira, Phys. Rev. C **83**, 034911 (2011) [arXiv:1011.3354 [nucl-th]];

- P. Bozek and W. Broniowski, Phys. Rev. Lett. **109**, 062301 (2012) [arXiv:1204.3580 [nucl-th]]; Presentation by W. Broniowski;
- [18] P. Bozek, W. Broniowski and I. Wyskiel-Piekarska, arXiv:1207.3176 [nucl-th]; Presentation by P. Bozek
- [19] S. Gavin and G. Moschelli, Phys. Rev. C **85**, 014905 (2012) [arXiv:1107.3317 [nucl-th]]; S. Gavin and G. Moschelli, Phys. Rev. C **86**, 034902 (2012) [arXiv:1205.1218 [nucl-th]]; Presentation by G. Moschelli
- [20] B. Schenke, S. Jeon and C. Gale, Phys. Rev. C **85** (2012) 024901 [arXiv:1109.6289 [hep-ph]]; M. Dion, J. -F. Paquet, B. Schenke, C. Young, S. Jeon and C. Gale, Phys. Rev. C **84** (2011) 064901 [arXiv:1109.4405 [hep-ph]];
- [21] G. Vujanovic, C. Young, B. Schenke, S. Jeon, R. Rapp and C. Gale, arXiv:1211.0022 [hep-ph]; Presentation by C. Gale
- [22] The ATLAS Collaboration, Conference note ATLAS-CONF-2012-049; Presentation by S. Mohapatra
- [23] Z. Qiu and U. W. Heinz, Phys. Rev. C **84** (2011) 024911 [arXiv:1104.0650 [nucl-th]]; Z. Qiu and U. Heinz, Phys. Lett. B **717** (2012) 261 [arXiv:1208.1200 [nucl-th]]; J. S. Moreland, Z. Qiu and U. W. Heinz, arXiv:1210.5508 [nucl-th]; Presentation by U. Heinz
- [24] E. Retinskaya, M. Luzum and J. -Y. Ollitrault, Phys. Rev. Lett. **108**, 252302 (2012) [arXiv:1203.0931 [nucl-th]]; Presentation by E. Retinskaya
- [25] M. Luzum and J. -Y. Ollitrault, arXiv:1210.6010 [nucl-th]; Presentation by M. Luzum
- [26] R. A. Lacey, N. N. Ajitanand, J. M. Alexander, J. Jia and A. Taranenko, arXiv:1202.5537 [nucl-ex]; R. A. Lacey, N. N. Ajitanand, J. M. Alexander, J. Jia and A. Taranenko, arXiv:1203.3605 [nucl-ex]; Presentation by R. Lacey
- [27] Z. Qiu, C. Shen and U. Heinz, Phys. Lett. B **707**, 151 (2012) [arXiv:1110.3033 [nucl-th]]; Presentation by Z. Qiu
- [28] D. Teaney and L. Yan, Phys. Rev. C **83**, 064904 (2011) [arXiv:1010.1876 [nucl-th]]; arXiv:1206.1905 [nucl-th]; Presentation by D. Teaney
- [29] A. Bilandzic, R. Snellings and S. Voloshin, Phys. Rev. C **83** (2011) 044913 [arXiv:1010.0233 [nucl-ex]]; KAamodt *et al.* [ALICE Collaboration], Phys. Rev. Lett. **105** (2010) 252302 [arXiv:1011.3914 [nucl-ex]]; Presentation by A. Bilandzic
- [30] S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72** (2012) 2012 [arXiv:1201.3158 [nucl-ex]]; S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72** (2012) 2012 [arXiv:1201.3158 [nucl-ex]]; S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1204.1409 [nucl-ex]; S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **109** (2012) 022301 [arXiv:1204.1850 [nucl-ex]]; Presentation by W. Li
- [31] K. Aamodt *et al.* [ALICE Collaboration], Phys. Rev. Lett. **107** (2011) 032301 [arXiv:1105.3865 [nucl-ex]]; L. Massacrier [ALICE Collaboration], arXiv:1208.5401 [nucl-ex]; I. Selyuzhenkov, J. Phys. G **38** (2011) 124167 [arXiv:1106.5425 [nucl-ex]]; Presentation by I. Selyuzhenkov